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# Nonlinear Wave Modulation and Time Reversal Tomography of Structural Defects

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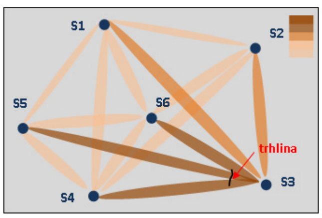
Classical ultrasonic tomography generally uses source signals of constant amplitude. Mostly linear characteristics like ultrasonic amplitude attenuation or time of flight in various directions are evaluated and used to structural defects imaging. On the other hand, more complex and nonlinear characteristics of elastic wave propagation, like 3rd harmonics etc. are starting to be also used for ultrasonic imaging e.g. in medicine, providing more sensitive indicators of small body changes and irregularities. Nonlinear parameters obtained by Nonlinear Elastic Wave Spectroscopy (NEWS) NDT techniques can give us better information about incipient damage zones than linear ones. The main advantage of NEWS consists not only in higher sensitivity but also in the ability to detect defects smaller than the ultrasonic wavelength. Some limitations of NEWS methodology are given by difficulties with more precise defects location when global excitation of larger or more complicated structures is applied. To overcome these constraints, further developments of NEWS techniques are desirable for nonlinear pseudo-tomography or tomography defects imaging. Two NEWS methods are considered: Nonlinear Wave Modulation Spectroscopy (NWMS) and Nonlinear Time Reversal Mirrors (NLTRM) with ESAM and DORT signal processing. Testing results, obtained on metallic and concrete parts illustrate performance of both procedures. The above described NDT procedures have been illustrated on the ASB aircraft part (Actuator Steering Bracket) subjected to 25000 loading cycles. No arising defects were indicated by traditional NDT methods, although the slightly enhanced acoustic emission (AE) activity was observed to be concentrated in the area depicted by crosslets. The ASB sample was tested by the above NLTRM procedure after 25000 cycles. Sine-pulse train of frequency 389 kHz and 30µs duration has been used in primary excitation. Damaged zones detected by AE and NLTRM are overlapping, which confirms high sensitivity of proposed nonlinear methodology. Advantage of tomography-like nonlinear methods is in their potentiality to acquire very complex information about the tested structure

## 1 Introduction

Tomography is the method of image reconstruction from many projections. The complete tomographic reconstruction procedure is based on reconstruction of ultrasonic wave fronts and requires exigent inverse problem solution [1]. As a here mentioned pseudo-tomography we denote easier method used for localization of zones where small defects most likely occure [2]. Its principle is illustrated by the schema and practical realization in Fig.1. Six transducers S1-S6 are placed on a testing sample with microscopic crack, and extracted nonlinear parameters, which are dependent on the wave paths, allocate the damaged zones (higher when crossing area with defects).



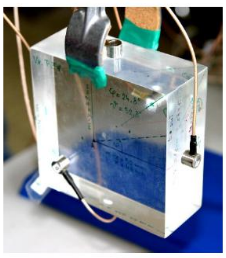



Fig. 1: Illustration of the pseudotomographic imaging of a cracked sample - schema andits practical realization on PMMA block with laser-induced crack

## 2. Multiplexed Frequency Mixing (NWMS) Tomography

The method, which is similar to simple two-frequency mixing NEWS procedure [3], has been already described in [4]. Two actuators and a sensor array properly dislocated on a structure are required to realize NWMS, and the high-voltage multiplexer is used to switch between piezoelectric transmitters and receivers. Two semi-continuous ultrasonic sine-wave signals of two relatively prime frequencies $f_{low}$, $f_{high}$ are transmitted to the tested sample with a constant or gradually growing amplitude, and their intermodulation products (side-bands around $f_{high}$, $2f_{high}$, $3f_{high}$) are evaluated as a measure of system nonlinearity. One or both signal transmitters (exciters) are successively multiplexed between receiving transducer array, and the most pronounced mixing products growth specifies defective zone. The technique allows global detection and zonal localization of crack-like damages in both relatively small and large extended structure parts of any form. We can suppose, that the observed mixing products are more pronounced when the excitation sources are closer to the damaged area and wave path of higher excitation frequency comprises present defects. Providing that the source of $f_{low}$ is not multiplexed (lower frequency is less attenuated), it can be placed at any position inside a tested region, and receiving transducers, multiplexed with the source of $f_{high}$ signal are properly dispersed along critical zones. Three or higher number of receiving/transmitting transducers should be used to cover relatively large structures, and their number depends on structure extent and attenuation. Maximal distance between transducers is determined from $f_{high}$ attenuation measurements. All transducers must be well fastened to the structure to avoid nonlinearity at their contact. The smallest detected defects are characterized by nonlinearity index ratio about 10 dB compared to the intact sample.

The calibration procedure comprises determination of appropriate transducers placement and excitation frequencies with respect to geometry and attenuation of the structure, and frequency bands of used transducers. Procedure can be realized by frequency wobbling or by the chirp pulse transmission. Excitation amplitude range and steps of amplitude growth must be also properly determined. The best practice is parallel calibration on an intact part. No other specific measurement conditions are needed except of ultrasonic and/or electric noise-free environment. All test conditions as structure mounting and border conditions must be the same as in calibration measurement on the comparative intact part.

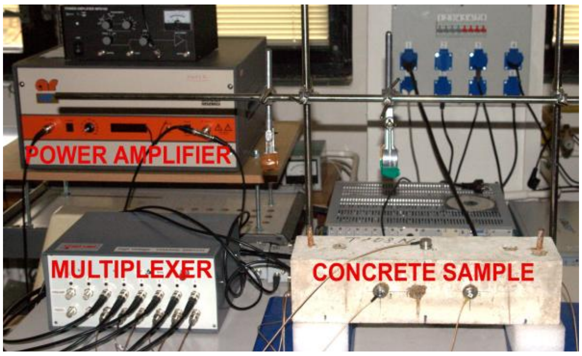



Fig. 2: NWMS test of reinforced concrete samples

Analysis of nonlinearity is performed in several steps. In a first step, frequency semilog-spectra of all signals received by all transducers are computed and amplitudes of $f_{low}$, $f_{high}$ harmonics and their intermodulation side bands are extracted Then, the extracted values are normalized on growing $f_{low}$ amplitude, and regression coefficients of their growth are evaluated (negative means decay and positive increase). The coefficients are compared to that obtained e.g. on calibration sample. The highest coefficients difference is selected as a nonlinearity index, and ordered to corresponding $f_{high}$ transmitters. Positive differences signalize damage presence, and their dependences on $f_{high}$ paths trace the damaged zones.

As an example, the NWMS test of steel-reinforced concrete samples of dimensions 100x100x400 mm is shown. Fig. 2 illustrates basic experimental arrangement: One exciter of = 45 kHz is affixed on the top of sample, and 6 transducers, multiplexed as signal receivers or $f_{high}$ = 217 kHz transmitters, are symmetrically attached to the side walls. Amplitude of $f_{low}$ sine-signal (amplified by a power amplifier) is successively raised-up in 8 steps. Third harmonics ($3f_{low}$) and intermodulation products ($f_{high} \pm 3f_{low}$) are evaluated from the frequency spectra of received signals. Matrixes of 3rd harmonics and frequency mixing products for both intact and damaged samples in dependence on growing $f_{low}$ amplitude are plotted in Fig. 3. Matrix columns correspond with signals received by transducers No. 1 to 6 when transducers numbered in rows are transmitting amplified signals of $f_{high}$.

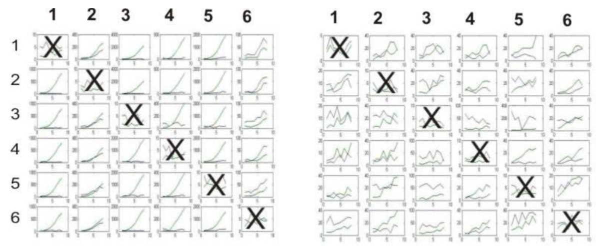



Fig. 3: Matrixes of 3rd harmonics (left) and frequency mixing products (right)for both intact (blue) and damaged (green)samples in dependence on growing $f_{low}$ amplitude

Nonlinear parameter $N_{mix} = k_1\, r(3\, f_{low} / 2\, f_{low}) + k_2{*}\, r(f_{high} \pm 3\, f_{low})$, is then evaluated from matrixes in Fig.3, where $k_1$, $k_2$ are weighting constants, and $r(..)$ means damaged to intact sample ratio of corresponding parameter growths (slopes) with growing $A(f_{low})$ amplitude. Resulting (symmetrized) matrix of nonlinear parameters $N_{mix}$ is visualized e.g. by ellipses along different wave-paths between multiplexed tranmitters/receivers, as it is shown in Fig.4 (pseudotomography imaging). The width and shading of ellipses is proportional to the nonlinear parameter Nmix.

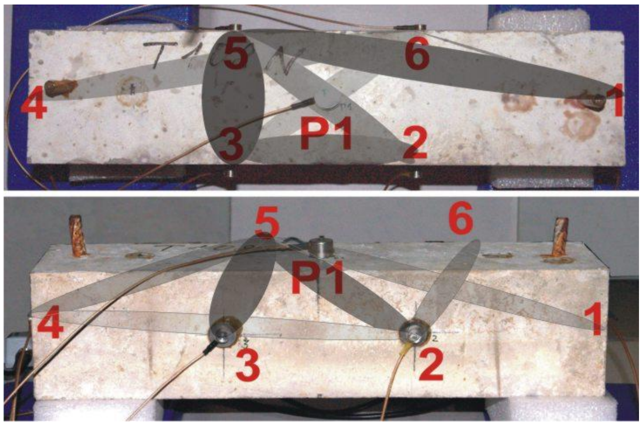



Fig. 4: NWMS pseudo-tomography imaging of damaged zones in reinforced concrete sample (corroded reinforcement separation).

Similar imaging based on damaged/intact nonlinear parameter growth ratio is illustrated on cyclic loaded steel "Actuator Steering Bracket" (ASB sample No.3 - the aircraft landing gear part mentioned previously in [5]), containing hair fatigue crack of 2.1 mm length after 123000 loading cycles. Frequencies $f_{low}$ = 62.9 kHz and $f_{high}$ = 389 kHz were used in frequency mixing test and the mixing product $2\, f_{high} \pm 3\, f_{low}$ is chosen for NWMS pseudo-tomography defective zone imaging in Fig. 5. Ellipses again indicated the cracked zone earlier than other NDT methods, except of acoustic emission monitored during fatigue test, embodying activity maxima in the same area.

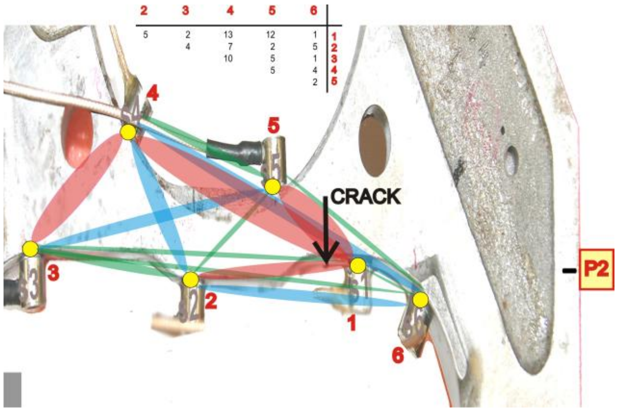



Fig. 5: NWMS pseudo-tomography imaging of thecracked zone in the ASB aircraft part subjected to fatigue loading.

# 3. Multiplexed nonlinear ultrasonic time-reversal (NLTRM) tomography

A multi-transducer variant of NLTRM [2] is similar to previous NWMS procedure with only one signal excitation. An array of piezoelectric transducers with appropriate frequency characteristics, allowing to be switched as actuator and/or sensor (up to 8 transducers were used in our tests) is again necessary. Required number of preamplifiers and filters (e.g. 20-60 dB with 20kHz high-pass filters) correspond with the number of attached transducers. An arbitrary waveform generator (20-1000 kHz) with remote amplitude control is used to structure excitation. A low distorsion power amplifier should be used for enough signal strength. Multi-channel high-voltage multiplexer, switching between actuators and sensors. Multi-channel digital signal recorder (at least 10 MHz/12 bit, 20 kSamples/channel), and driving computer.

NLTRM procedure described in [2] can be substantially simplified by using the ESAM (Excitation Symmetry Analysis) [7,8,9] to extract 3rd order nonlinearities from spectral matrices along the different wave-paths. When more defects are present in the damaged structure, necessary Time Reversal (TR) iteration process is replaced by the DORT (Decomposition of Time-Reversal Operator) method (detailed in [6]) applied on TR signals to separate individual defects and enhance signal to noise ratio.

The method can be used as global, covering the whole tested structure, and damaged zone localization is more straightforward than in the case of NWMS procedure. Test results shown that derived nonlinear parameters are dependent on the wave path along damaged zone (higher when crossing area with defect). The transducers should be placed at positions surrounding tested area (if possible in a quasi-symmetric way). Four or higher number of transmitting/receiving transducers are necessary to cover relatively large structures. Laser interferometer scanning can be often used instead of receivers multiplexing in simpler situations when tested part is not completely hidden [7]. Higher number of transducers gives better results and more accurate defect location. Maximal distance between transducers depends on structure attenuation in selected frequency band. All transducers must be well mounted on the structure surface. Important factors in performing tests are proper selection of primary excitation pulse frequency (or frequency band), signal waveform, and amplitude range. Most suitable frequencies can be determined by calibration procedure (chirp pulse or frequency sweeping). Excitation amplitudes (with max/min ratio 5-10) can be lower than in NWMS, but sufficient to excite distant transducers. The amplitudes should be enough high as to excite structural nonlinearity, but not exceeding certain limits, given by nonlinearities of devices (transducers, preamplifiers and power amplifiers). Another variable affecting results is the length of recorded signal. It should be long enough as to ensure good spectral resolution.

# 4. Pseudo-tomography imaging using ESAM-DORT

Newly developed combined ESAM & DORT procedure [6] consists of the following main steps:

1. Three phase shifted input signals $x_{kj}(t)$ are used to excite the structure at each of $S_j$ transducers
2. Matrixes $E^k_{ij}(t)$ of corresponding responses are measured; each $ij$-element represents signal received by transducer $Si$ during the transmission of $x_{kj}(t)$ from transducer $S_j$. Each diagonal element $E^k_{ii}(t)$ contains the input signal $x_{kj}(t)$. The response matrixes are further processed by the DORT method:
3. Spectral matrixes are used for the construction of the time-reversal operators: $T^k(\omega) = E^k{*}(\omega)\, E^k(\omega)$, $k$ = 1,2,3. Operators $T^k$ are then diagonalized. Their eigenvalues correspond to isolated defects
4. To detect only the strongest defect, choose for each operator $T^k$ one eigenvector corresponding to the maximal eigenvalue (vector $v_k$). Vectors of limit signals for operators $T^k$ are obtained by calculation
5. Spectra of these signals are obtained as $r_k(\omega) = 1/\lambda_k(\omega)\, E^k{*}(\omega)\, v_k(\omega)$
6. Similarly to the first steps, matrixes $D^k(t)$ are measured; input signals are given by the limit vectors $v_k$
7. Element $D^k_{ij}(t)$ corresponds to signal received by the transducer $j$ during the signal transmission from transducer $i$ after infinite iterations of TR process on input signal $x_k(t)$.
8. Fourier transform is applied to matrixes $D^k(t)$, and summation $ED_{ij}(\omega) = D^1_{ij}(\omega) + D^2_{ij}(\omega) + D^3_{ij}(\omega)$, $i,j = 1 \ldots 6$ is performed. Elements EDij(ω) correspond to cubic parts of response spectra between $S_i$ and $S_j$
9. Sum of the maximal amplitudes of spectra $ED_{ij}(\omega)$ and $ED_{ji}(\omega)$ gives a parameter corresponding to the probability of crack presence on trajectory between $S_i$ and $S_j$.

Extracted nonlinear parameters are dependent on the wave paths along damaged zones (higher when crossing area with defect), which allow pseudo-tomography imaging of defective zones.

The above described NDT procedure can be again illustrated on the ASB aircraft part (Actuator Steering Bracket), but sample No.5, subjected only to 25000 loading cycles. No arising defects were indicated by traditional NDT methods, although the slightly enhanced acoustic emission activity was observed to be concentrated in the area depicted by crosslets in Fig.6.

The ASB sample was tested by the above NLTRM procedure after 25000 cycles. Sine-pulse train of frequency

389 kHz and 30μs duration has been used in primary excitation with variable signal phases $\phi_1=0$, $\phi_2=2\pi/3$, $\phi_3=-2\pi/3$, $\phi 4=\pi/2$. Corresponding responses $y(t)$ were measured (assumed composed of linear, quadratic, and cubic terms):

$$y(t) = NL[x(t)] = N_1x(t) + N_2x^2(t) + N_3x^3(t) \qquad (1)$$

at each transducer, and ESAM - DORT method was applied. to extract 3rd order nonlinearity parameter. Pseudotomography imaging of extracted nonlinear parameter $N_3^2$ matrix (normalized and symmetrized) is illustrated in Fig. 6. Transducers are numbered 1-6 and corresponding transmitter/receiver matrix of $N_3^2$values is shown. By comparing with AE localisation (red crosses in green square on Fig. 6), there is evident that probably damaged zones detected by AE and NLTRM are overlapping, which confirms high sensitivity of proposed nonlinear methodology. Advantage of tomography-like nonlinear methods is in their potentiality to acquire very complex information about the tested structure.

| RECEIVER \ TRANSMITTER | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | _ | 103 | 102 | 27 | 11 | 50 |
| 2 | | _ | 183 | 78 | 18 | 76 |
| 3 | | | _ | 34 | 14 | 77 |
| 4 | | | | _ | 7 | 21 |
| 5 | | | N3$^2$ | | _ | 26 |

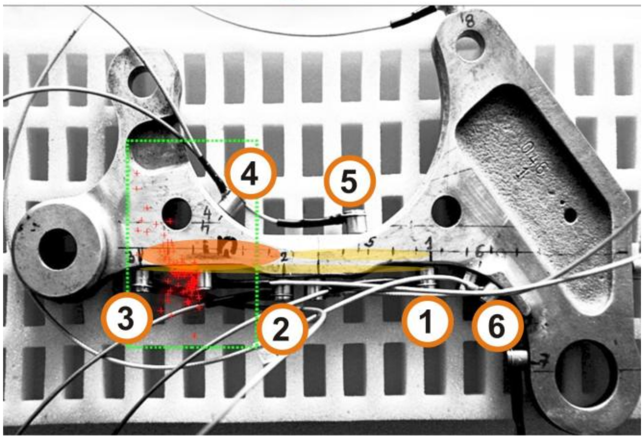



Fig. 6: ASB aircraft part with depicted zone of enhanced acoustic emission activity during the fatigue cycling. NLTRM pseudotomgraphy imaging of potentially zone with arising defect signalized already by acoustic emission.

## 5 Conclusion

Described pseudotomography imaging procedure allows to determine the wave paths (zones) with the most probable defects locations. For detailed specification of the defect position on each wave path, the concept of virtual transducers may be used [8]. Based on the evaluation of the nonlinearity level we can choose one or few paths with the strongest nonlinear parameters to perform measurements with “virtual transducers”. The main idea of that is in the generation of a single excitation signal, which replaces many separate excitations. This signal is created by a sum of the excitations of all the transducers, which are time-shifted according to transducers positions. The appropriate time-shifts are calculated according to the material celerity. The whole concept is still a subject of further research.

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